This is the author's version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication.
The final version of record is available at http://dx.doi.org/10.1109/TASC.2016.2637318

AC loss reduction in multifilamentary coated conductors with transposed filaments

A. Ben Yahia, X. Li, M. Majoros, M. D. Sumption, V. Selvamanickam

***Abstract*— Filamentization has been shown to be an effective method in reducing magnetization AC loss of RE-Ba-Cu-O (REBCO) coated conductors. We have used a laser striation method followed by selective electroplating of copper to fabricate fully-stabilized multifilamentary REBCO tapes with 12, 24 and 46 filaments. While expected levels of AC loss reduction has been confirmed in short segments of such multifilamentary tapes, electric coupling between the filaments of long tapes needs to be suppressed by transposition of the filaments. In this work, a technique was developed and implemented to reduce AC losses in REBCO multifilamentary coated conductors through a new design that allows to transpose the filaments without any mechanical twisting. The process consists of patterning REBCO tapes by laser ablation followed by partial insulation and bonding. A two-fold reduction of AC magnetization losses was achieved in the transposed multifilamentary REBCO tape when subject to an external perpendicular magnetic field at frequencies between 50 and 200 Hz and peak field values up to 88 mT. The filament-to-filament resistance and its effect on the coupling has also been investigated.**

***Index Terms*—AC losses, coated conductor, interfilamentary resistance, multifilamentary, reel-to-reel, transposition .**

I. Introduction

THE IMPROVEMENT of the performance of high temperature superconductor (HTS) coated conductors (CC) by the addition of artificial pinning centers [1], [2] makes them very attractive for use in DC applications. However, in AC applications, the tape geometry of the CC with a very thin superconducting layer and a high aspect ratio makes AC losses a significant problem in practical applications. These losses can be significantly reduced by dividing HTS tapes into several narrow filaments with lower aspect ratio [3].

Filamentization has been shown to be an effective method in reducing magnetization AC loss of RE-Ba-Cu-O (REBCO) coated conductors and several techniques have been investigated such as mechanical scribing [4], inkjet printing [5], [6] and laser ablation [7], [8]. Some of these methods have been shown to be scalable for the production of long-length multifilamentary tapes [9].

Although expected AC losses reduction has been shown over short segments of multifilamentary tapes [10], coupling losses need to be suppressed by transposing the filaments in order for this technique to be effective over long lengths [11]. Some solutions based on tape cabling techniques [12] have been proposed to solve the coupling issue where the tape is bend and/or twisted to achieve the transposed configuration. Other solutions based on a zig-zag pattern [13] have been proposed but this configuration imposes a reduction of the critical current just by geometrical considerations.

In this work, we have used a laser striation method followed by selective electroplating of copper to fabricate fully-stabilized multifilamentary REBCO tapes with different number of filaments. In addition, we have developed and implemented a new patterning design shown in Fig. 1, allowing to transpose the filaments and thus significantly reducing the AC losses without any mechanical twisting. We have also examined the quality of the striation method by investigating the filament-to-filament (F2F) resistance and its effect on the coupling.

II. Experimental

A. The filamentization process

The REBCO tapes used in this work were 12 mm wide CC tapes from Superpower Inc. The conductor consists of a buffer stack made of Al_2O_3, Y_2O_3, MgO, and $LaMnO_3$ layers, deposited over an electro-polished Hastelloy substrate. The REBCO layer is ~ 1.6 µm thick produced by metal organic chemical vapor deposition (MOCVD). The tape is then coated with a 2 µm silver layer on the REBCO side and a 1.8 µm layer on the substrate side.

The striation was made by laser ablation. The diode-pumped femtosecond laser used had a pulse duration of 350 fs, a repetition rate of 200 kHz, a wavelength of 1033 nm and a total power of 4.1 W. The produced grooves cut through the silver, REBCO, buffer stack and partially the Hastelloy and they are in average ~9.5 µm deep and ~67 µm wide. Following the striation, the tapes were oxygenated for 2 h at 550 °C allowing the exposed Hastelloy to oxidize and thus the formation of a high-resistance oxide on the groove surface which makes the selective electroplating afterward possible [14]. The samples each originally 14 cm long were electroplated in beaker with an

This work was partly funded by the Army Research Laboratory.

Anis Ben Yahia is with Department of Mechanical Engineering, Texas Center for Superconductivity and Advanced Manufacturing Institute, University of Houston, Houston, TX 77204, USA, e-mail: abenyahia@uh.edu.

Xiao-Fen Li is with Department of Mechanical Engineering, Texas Center for Superconductivity and Advanced Manufacturing Institute, University of Houston, Houston, TX 77204, USA.

Milan Majoros is with Materials Science Department, The Ohio State University, Columbus, OH, United States.

Michael D. Sumption is with Materials Science Department, The Ohio State University, Columbus, OH, United States.

Venkat Selvamanickam is with Department of Mechanical Engineering, Texas Center for Superconductivity and Advanced Manufacturing Institute, University of Houston, Houston, TX 77204, USA.

acid-free $Cu(NO_3)_2$ solution to deposit ~25 µm of Cu stabilizer. A standard four-probe method was used for I_c measurements with 1 µV/cm criterion. Then, a 3 cm piece was cut from the middle of each sample and their AC losses measured. Magnetization AC loss measurements were performed using the pickup coil method at frequencies between 40 and 500 Hz at 77 K. The four-probe method was also used to perform transverse resistivity measurements. Fig.1 shows photographs of a 12-filament sample after copper electroplating and the 24 and 46 filament samples as striated (before copper plating).

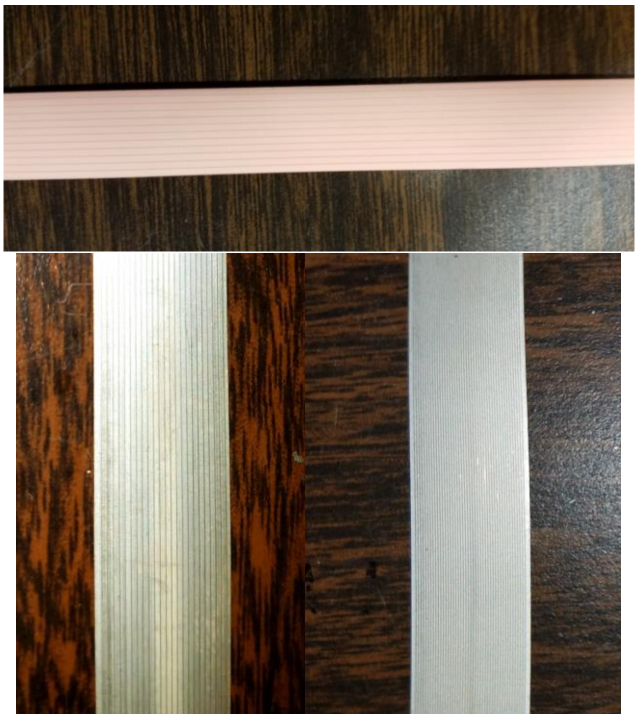

Fig. 1. Photograph of (top) a 12-filament sample after copper electroplating, (left) a 24 and (right) a 46 filament-tape as striated.

B. Implementation of the transposition design

The pattern used to achieve the transposition is illustrated in Fig. 2. Each single tape is made of four 3 mm wide filaments, comprised of a straight section varying from 5 to 10 cm long and a 5 cm area where we have the transposition pattern consisting of "L-shaped" grooves. These tapes are set face to face and joined only at their edge filaments. The current flow in such configuration is described in figure Fig. 1b.

In order to achieve that, we first coat the unconnected region of the transposition area with an Y_2O_3 insulating layer. A mask made with Kapton tapes covers the rest of the sample while part of the overlap area is dip coated into a solution of YAc_3 in methanol and diethanolamine. The deposited layer is then cured at 400 ^{0}C for 0.5h in O_2 flow. Additionally, a thin silver layer is deposited on the connecting regions at the edge of the tape to compensate for the thickness difference. Silver to silver diffusion bonding is used to join the samples without the use of any soldering material. The tapes were held face to face with a pressure of ~ 15 MPa, heated and held at 500 ^{0}C for 2h in O_2 flow. The joint resistance for these samples was measured to be around 0.6 µΩ.cm^2. Finally, the resulting joint was electroplated with copper in a beaker using a $Cu(NO_3)_2$ methanol-based solution.

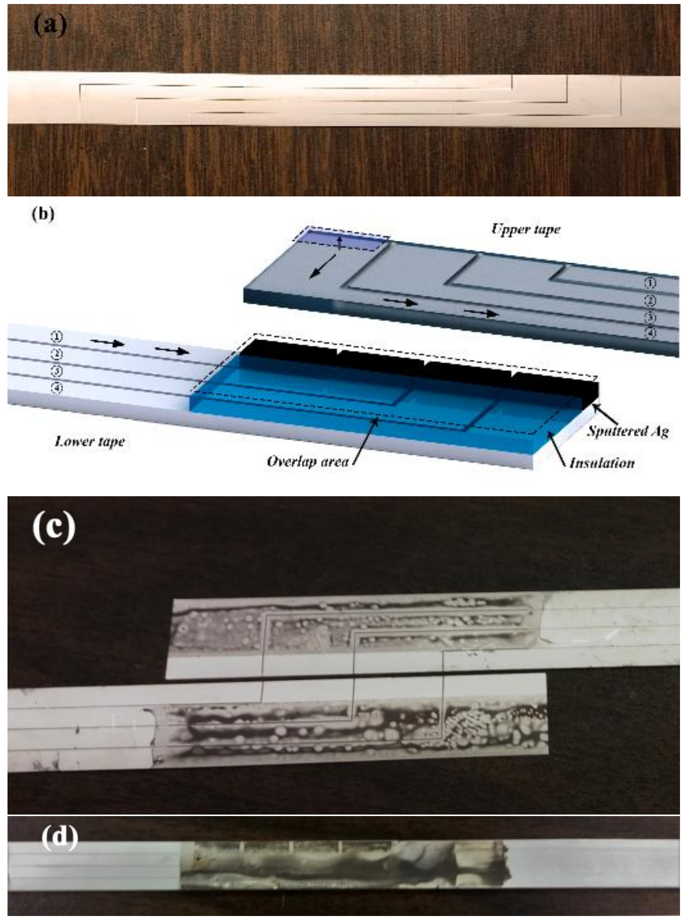

Fig. 2. (a) Photograph of the tape used in the transposed configuration (b) Representation of the transposed multifilament tapes. Arrows shows the current path from filament 1 to filament 4. The tapes are joined face-to-face (not all the layers are represented). (c) Photograph of the tapes before joining, the top tape is rotated by 180 degrees and pressed face to face with the lower tape. (d) Photograph of the transposed tapes after joining.

Ac loss was measured using a pick-up coil magnetometer immersed in liquid nitrogen [15], [16]. The field was applied by a race track coil with a homogeneous field region over a length of 15 cm. The applied magnetic field frequency ranged from 50 to 200 Hz with maximum amplitude of 88 mT.

III. Results and Discussion

A. AC loss reduction by filamentization

The 12, 24 and 46 filament tapes were oxidized and electroplated in beaker with a 25 µm thick Cu stabilizer. The critical current of the original non-striated tape was 410 A, while that of the striated ones was respectively 360, 310 and 270 A for the 12, 24 and 46 filaments. Most of the I_c degradation is due to the superconductor volume removal (i.e. ~6.1% for 11 grooves and ~30.1% for 45 grooves), while an additional 5 to 9% is lost during the remainder of the process mainly during the oxygenation part where some elements of the Hastelloy could diffuse to the edge of the filament [14].

Fig. 3 shows the results from the magnetization AC loss measurement at a frequency of 100 and 500 Hz on 3 cm long pieces of the 12, 24 and 46 filament copper-stabilized tapes. Results from the non-striated original tape are also shown for reference. Based on the Brandt model [3], the AC loss per cycle per unit length is expected to decrease by an order equal to the number of filaments as shown in (1).

$$\frac{P}{\mu_0 I_c^2} = \frac{wH_a}{I_c}\left[\frac{2}{x}\ln(\cosh x) - \tanh x\right] \quad (1)$$

where $x = B_a/B_p = (\pi H_a w)/I_c$ and w is the width of the tape in the non-striated case and the width of the filament for the multifilament tapes.

It can be seen that with increasing field, the AC loss behavior converges towards the Brandt model for each striated case. At lower fields, the behavior departs from the model and the losses become closer to that of a non-striated tape, indicating possible magnetic coupling at low fields [17]. The presence of a small frequency dependence of the AC loss, especially at higher fields, indicates also the presence of some electrical coupling between the filaments.

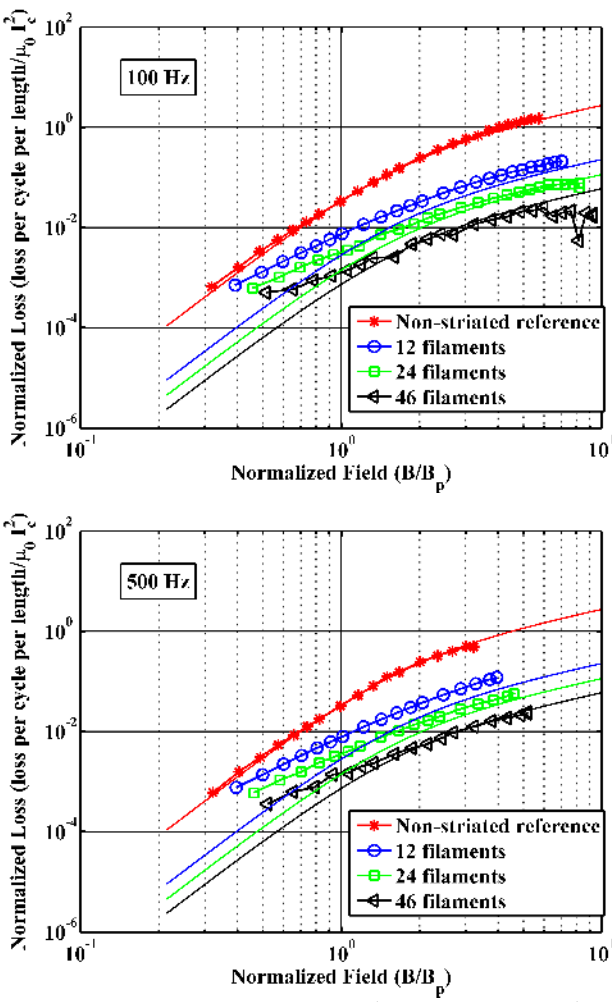

Fig. 3. Normalized magnetization ac losses for all samples. Top is for 100 Hz and bottom is for 500 Hz. The solid lines represent the Brandt model for each configuration (non-striated, 12,24 and 46 filaments).

In order to characterize the striation quality and investigate the possible coupling reasons, a measurement of the filament-to-to filament (F2F) transverse resistivity was carried on two 12-filament tapes; the first is a striated tape only oxidized and the second had an additional 25 µm of Cu electroplated on top. The average F2F resistance for the Ag tape was 158.1 mΩ/cm and 1.3 mΩ/cm. The reason for such a big difference between the two tapes is that during the selective electroplating process, even though the center of the groove remains copper free, the copper grows also on the edge of the filaments [9] creating a less resistive path for the current than that only through the buffer's oxides to reach the Hastelloy and then the next filament. Before electroplating, for the current to flow from one filament to another it has to pass from the superconductor through the buffer layers into the Hastelloy and then reach the other filament again through the buffers oxides. For the Cu-electroplated samples, because of the copper lateral growth on the edge of the groove, there is a second path for the current to pass from one filament to the other, in parallel to the one through the buffer layers. The second path is from the superconducting layer to the silver, copper and then to the Hastelloy on the bottom of the groove. In fact, the groove that is initially 67 µm wide becomes only 20~25 µm wide after electroplating because of copper growth on the edges. This second current path explains such a drop in the F2F resistance after Cu-electroplating.

Fig. 4 shows the results of the F2F resistance measurement for the two tapes. It shows that the values of the F2F resistance spreads over almost two orders of magnitude even for the tape before electroplating. This indicates that during the laser ablation some of the removed material get redeposited on the edges of the grooves. While the deep grooves guarantee a complete cut through the superconducting layer, the round smooth edges of these grooves create a less resistive path more favorable to coupling. This was further confirmed by EDX analysis of the groove across its width and the discovery of silver up to 15% at the edge of the grooves.

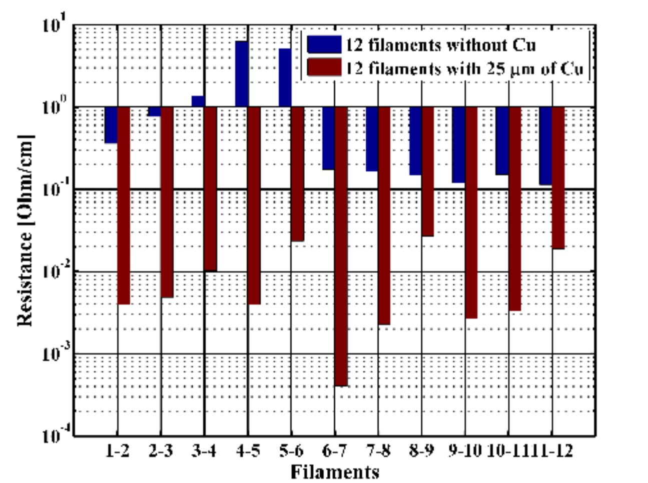

Fig. 4. Filament-to-filament resistance for 12-filament tape with and without copper stabilizer.

B. AC loss reduction by transposition

Transposed samples were made in this work using two 4-filament tapes each 105 mm long. The two tapes consisted of a 5 cm long area with the transposition pattern (shown in Fig. 2) continued with 4 straight filaments on the remaining 5.5 cm resulting in a 16 cm sample with one transposition at its center.

Two transposed samples were measured, T1 as described above and T2 coupled over 3 cm at both ends with 25 µm of copper. This was achieved by first sputtering a thin layer of silver on the ends to enable electroplating of copper. Sample T2 was made in such way to exclude the possibility that over the available sample measurement length, the F2F resistance could be high enough to prevent electrical coupling. Additionally, two straight 4- filament samples were measured; S1 is a 4-filament sample coupled at both ends with copper similar to T2 and S2 is without any copper.

Fig. 5 shows the results of the magnetization ac losses for these four samples. It can be seen that S1 behaves as fully coupled and its losses are similar to that of a non-striated tape. Sample S2, however, is in fully decoupled configuration showing a 4-fold reduction of AC losses at 50 and 100 Hz compared to a normal tape and exhibits the same behavior of the multifilament tapes discussed in the previous section.

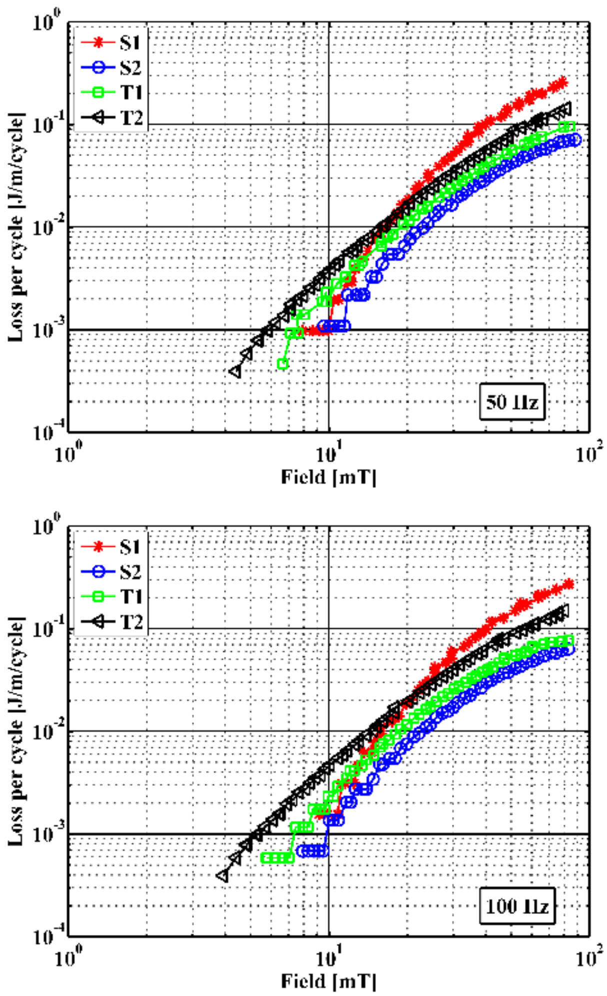

Fig. 5. Magnetization ac losses vs applied field. S1 is a straight 4-filament tape with 3 cm completely covered (groove included) with 25 µm copper on both ends, S2 is a straight 4-filament tape without copper, T1 is a transposed sample without copper and T2 is transposed sample with 3 cm completely covered (groove included) with 25 µm copper on both ends. Top plot is for a frequency of 50 Hz and bottom is for 100 Hz.

Sample T1 shows ~25% higher loss than S2. This is due to the additional superconductor volume present in the overlap area. Besides, the frequency-independent behavior suggest that the sample is fully decoupled and the slight loss reduction at higher fields at 100 Hz is due to sample heating because the sample was not coated with copper. Sample T2, which was selectively electroplated with 25 µm of copper except for the both ends where the grooves are completely covered with copper (similar to S1) ensuring that the mechanism allowing the decoupling of the filaments to be only the transposition of the filaments. The measured loss is half of that of S1 but slightly higher than that of T1 with a frequency-dependent component. The possible reason for this is that the 3 cm area used to couple the filaments is longer than necessary resulting in part of the sample behaving as a normal tape and generating significant losses.

It should be noted also that the results for samples T1 and T2 are in a qualitative agreement with ac losses of CORC cables wound using a single tape 12 mm wide and wound using three 4 mm tapes [16]. For low fields, the ac losses increase proportionally to the third power of the magnetic field amplitude followed by a linear dependence at higher fields. The observed crossover in the AC losses have been attributed to better screening abilities of the non-striated tape (in this case the fully coupled 4-filament tape behaving as a non-striated tape) in the low-field region.

IV. Conclusion

In this work, a laser striation process followed by selective electroplating has been used to produce multifilamentary tapes with different number of filaments. Expected reduction in AC losses has been achieved.

Moreover, a new design allowing filaments transposition have been presented and implemented. The obtained transposed multifilament samples show promising AC losses reduction. In addition, a similar design could be used with a higher number of filaments to reduce the loss even more.

References

[1] V. Selvamanickam *et al.*, "Enhanced and uniform in-field performance in long (Gd, Y)–Ba–Cu–O tapes with zirconium doping fabricated by metal–organic chemical vapor deposition" *Supercond. Sci. Technol.* 23 (2010) 014014 (6pp).

[2] V. Selvamanickam *et al.* "High critical currents in heavily doped (Gd,Y)$Ba_2Cu_3O_x$ superconductor tapes" *Applied Physics Letters* 106, 032601 (2015).

[3] E. H. Brandt and M. Indenbom, "Type-II-superconductor strip with current in a perpendicular magnetic field," *Phys. Rev. B*, vol. 48, pp. 12893–12906, 1993.

[4] G. Majkic *et al.*, "AC loss filamentization of 2G HTS tapes by buffer stack removal," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 3297–3300, Jun. 2011.

[5] X. Cai, I. Kesgin, R. Schmidt, Y. Chen, and V. Selvamanickam, "Completely Etch-free fabrication of multifilamentary coated conductor using inkjet printing and electrodeposition," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, Jun. 2013, Art. ID. 6603005.

[6] R. C. Duckworth, M. P. Paranthaman, M. S. Bhuiyan, F. A. List, and M. J. Gouge, "AC losses in YBCO coated conductor with inkjet filaments," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 3159–3162, Jun. 2007.

[7] G. A. Levin *et al.*, "Multifilament YBa2Cu3O6+x-coated conductors with minimized coupling losses," *Appl. Phys. Lett.*, vol. 89, no. 1, Jul. 2006, Art. ID. 012506.

[8] H. Okamoto *et al.*, "AC loss properties in YBCO model coils for loss reduction," *Phys. C, Supercond.*, vol. 468, no. 15–20, pp. 1731–1733, Sep. 2008.

[9] X. Cai, I. Kesgin, and V. Selvamanickam, “Reel-to-Reel Selective Electroplating of Cu Stabilizer for Multifilamentary Coated Conductors,” *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, June 2015.

[10] I. Kesgin, G. A. Levin, T. J. Haugan, and V. Selvamanickam, “Multifilament, copper-stabilized superconductor tapes with low alternating current loss,” *Applied Physics Letters* 103, 252603 (2013).

[11] C. E. Oberly, G. L. Rhoads, P. N. Barnes, L. Long, D. J. Scott and W. J. Carr Jr., “The importance of interfilamentary barrier resistance in YBCO coated conductor to minimize ac losses,” *AIP Conf. Proc.* 614, 621 (2002).

[12] J Šouc *et al.*, “Low AC loss cable produced from transposed striated CC tapes,” *Supercond. Sci. Technol.* Vol. 26, no. 7 (2013).

[13] D. Abraimov *et al.*, “Significant reduction of AC losses in YBCO patterned coated conductors with transposed filaments,” *Supercond. Sci. Technol.* Vol. 21, no. 8 (2008).

[14] I. Kesgin *et al.*, “Influence of Oxygenation in Copper Stabilized Multifilamentary 2G HTS Tapes Made by Selective Electroplating and Laser Ablation,” *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, Jun. 2015, Art. ID. 6601005.

[15] M. D. Sumption, S. Kawabata and E. W. Collings, “Ac loss in YBCO coated conductors exposed to external magnetic fields at 50-200 Hz,” *Physica C: Superconductivity and its applications*, vol. 466, Issue 1, p. 29-36.

[16] M. Majoros, M. D. Sumption, E. W. Collings and D. C. van der Laan, “Magnetization losses in superconducting YBCO conductor-on-round-core (CORC) cables,” *Supercond. Sci. Technol.* Vol. 27, no. 12 (2014).

[17] M. Marchevsky, E. Zhang, Y. Xie, V. Selvamanickam, and P. G. Ganesan, “AC losses and magnetic coupling in multifilamentary 2G HTS conductors and tape arrays,” *IEEE Trans. Appl. Supercond*., vol. 19, pp. 3094–3097, 2009.